New Frontiers in Ceramic Composites: Tunable Electromagnetic Interference Shielding via Metal-Free Negative Permittivity in $SnO_2/LaNiO_3$ Nanocomposites

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1. Relative Permittivity Analysis of Pure SnO_2 and $LaNiO_3$

The frequency-dependent relative permittivity of pure SnO_2 and $LaNiO_3$ is presented in Fig. S1. As observed in Fig. S1(a), pure SnO_2 exhibits typical insulating behaviour, with the dielectric permittivity (ε') in the range of 10^2 - 10^3. This characteristic response is expected for wide-bandgap semiconductors like SnO_2, where the dielectric constant decreases with increasing frequency due to the limitation of dipolar polarization at higher frequencies.

On the other hand, $LaNiO_3$, as shown in Fig. S1(b), exhibits a different behavior, characterized by negative permittivity of the order of 10^7. The negative permittivity is indicative of metallic-like conduction and plasmonic effects within the material, making it a potential candidate as an alternative for traditional metals. Furthermore, the fitted data (red curves in Fig. S1(b)) exhibit a strong frequency-dependent response, consistent with Drude-like behavior in $LaNiO_3$, supporting the free-electron conduction mechanism. Overall, the different dielectric responses of SnO_2 and $LaNiO_3$ highlight the fundamental difference between insulating and conducting materials, reinforcing the role of $LaNiO_3$ as a highly conductive and tunable component in composite systems.

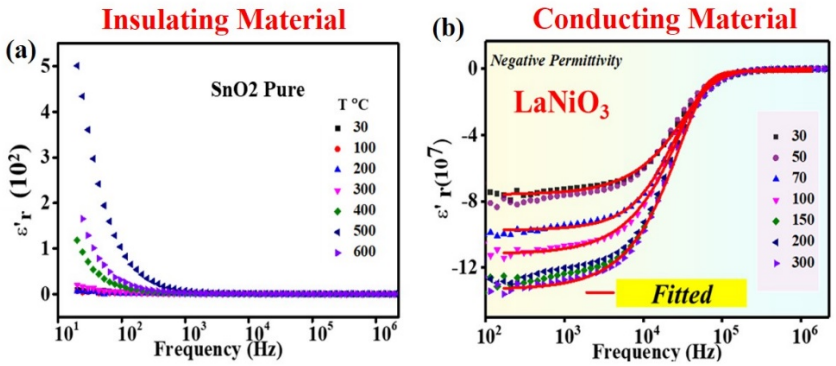

Figure S1. Frequency-dependent relative permittivity of (a) pure SnO_2, exhibiting typical insulating behavior with a permittivity range of 10^2 - 10^3, and (b) $LaNiO_3$, demonstrating negative permittivity with a high magnitude (~10^7), indicative of metallic conduction and plasmonic effects. The contrasting dielectric properties highlight the fundamental difference between the two materials.

2. X-ray Photoelectron Spectroscopy (XPS) Analysis

To investigate the chemical states of the elements, present in the composite, XPS measurements were conducted, and the corresponding spectra are presented in Fig. S2 A crucial observation from the data is that there is no significant shift in the binding energies or their positions. This confirms the absence of any strong chemical interactions between SnO_2 and $LaNiO_3$, indicating that the composite formation primarily involves physical mixing rather than chemical bonding.

Fig. S2(a) displays the Ni 2p XPS spectra, where characteristic peaks corresponding to Ni^{3+} $2p_{3/2}$ and Ni^{2+} $2p_{3/2}$ are observed. Additionally, satellite peaks (sat.) associated with these oxidation states appear around 872 eV for the Ni^{3+}/ Ni^{2+} $2p_{1/2}$ states [1]. The presence of both oxidation states indicates a mixed-valence nature of Ni in the composite, which is consistent with the expected electronic structure of $LaNiO_3$. Notably, a similar spectral profile is observed for SLN30, with no major differences in peak positions or intensities, reinforcing the conclusion that the $LaNiO_3$ phase remains chemically unaltered in the SnO_2 matrix.

Fig. S.2(b) illustrates the Sn 3d core-level spectra, where two distinct peaks at approximately 486.6 eV and 495 eV correspond to Sn^{4+} $3d_{5/2}$ and Sn^{4+} $3d_{3/2}$, respectively [2]. The sharp and symmetric nature of these peaks confirms the dominance of the Sn^{4+} oxidation state, indicating that the SnO_2 phase remains consistent. The binding energy values align well with previously reported values for SnO_2, further confirming the stability of the tin oxide phase in the composite[2].

Overall, the XPS analysis reveals that no noticeable chemical reaction occurs between SnO_2 and $LaNiO_3$, and both phases retain their inherent oxidation states in the composite system.

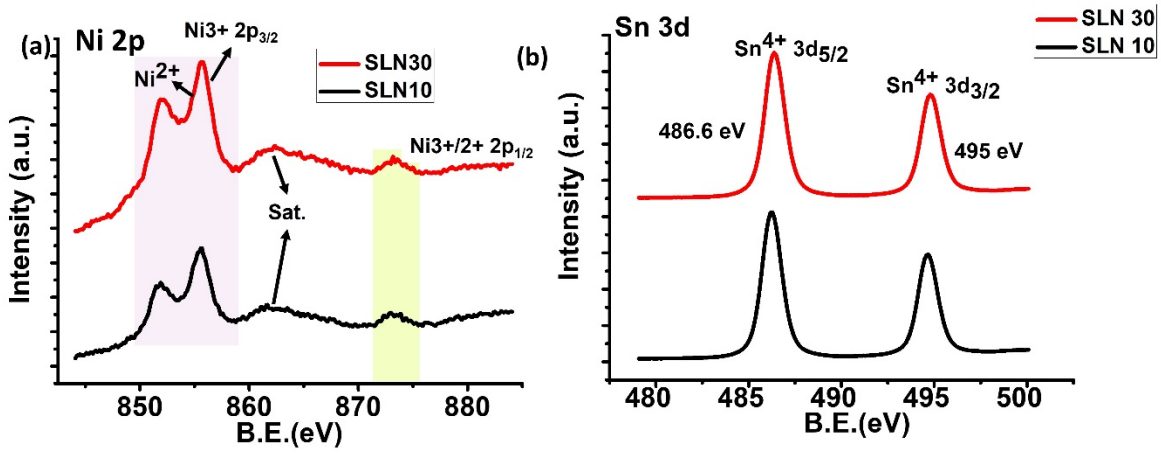

Figure S2. XPS spectra of the prepared composites. (a) Ni 2p spectrum showing Ni^{3+} and Ni^{2+} oxidation states along with their satellite peaks, confirming the mixed-valence nature of Ni in the composites. (b) Sn 3d spectrum displaying Sn^{4+} peaks, indicating the chemical stability of SnO_2 in the composite without significant interaction with $LaNiO_3$.

References

1. Sønsteby, H. H., Skaar, E., Fjellvåg, Ø. S., Bratvold, J. E., Fjellvåg, H., & Nilsen, O. (2020). A foundation for complex oxide electronics-low temperature perovskite epitaxy. *Nature communications*, *11*(1), 2872.
2. Babu, B., Reddy, I. N., Yoo, K., Kim, D., & Shim, J. (2018). Bandgap tuning and XPS study of SnO2 quantum dots. *Materials Letters*, *221*, 211-215.